(p,d) Pickup Reactions in Light Nuclei*†

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Using a thin proportional counter as a velocity selector in conjunction with a NaI crystal to measure energy, deuterons from proton-induced reactions in some light nuclei were studied. The detection system was capable of presenting an essentially undistorted spectrum of deuterons in the presence of protons of the same energy and considerably more intense. Angular distributions of deuterons from $C^{13}(p,d)C^{12}$, $N^{14}(p,d)N^{13}$, $N^{15}(p,d)N^{14}$, $F^{19}(p,d)F^{18}$, $Mg^{25}(p,d)Mg^{24}$, and $P^{31}(p,d)P^{30}$ were taken. Butler curves were calculated to fit the experimental distributions and level widths extracted.

I. INTRODUCTION

THE success of the Butler theory in the interpretation of forward peaking in particle exchange reactions has served as a stimulus to a great deal of experimentation. Attention was originally on the shape of the spectrum from which spins and parities of associated levels could be deduced. The reaction cross section has more recently been made use of to test the nature of nuclear wave functions. Information about stripping reaction cross sections augments that obtained from "static" experiments such as level structure, beta-decay ft values, and nuclear magnetic and quadrupole moments. The results reported here constitute a study of (p,d) angular distributions which involve states of light nuclei for which analysis of the cross section contributes significantly to nuclear spectroscopy.

Restriction of the investigation to light nuclei was a consequence of the rapidly diminishing cross section for (p,d) reactions with increasing atomic number of the target nucleus as well as the decrease in the spacing of low-lying levels of the residual nucleus. Attention was focused upon those reactions which led to resolvable deuteron groups, although in several instances a group containing a contribution from more than one level of the residual nucleus was studied. Angular distributions were in most cases taken over the forward angles only since the plane-wave Butler theory gives a good fit to the data only at small angles and interest was primarily in spectroscopic level parameters rather than details of the reaction mechanism. No attempt was made, except in the $N^{15}(p,d)N^{14}$ experiment, to check details of the angular distribution as a function of incident proton energy which was in the range 16.5 to 18.5 Mev. The proton beam spread was about 200 kev.

Since (p,d) pickup reactions lead to a different set of levels than the complementary stripping reaction, it is perhaps surprising that so few of the former have been investigated. There are several practical reasons for this, however. The Q of a (p,d) reaction is nearly always negative and of the order -8 Mev which means that these experiments are inaccessible to the majority of Van de Graaff generators and proton cyclotrons in use. For the (d,p) case, low-energy deuterons will produce protons of higher energy which may be distinguished from background quite easily. For (p,d) reactions the situation is reversed: high-energy protons producing low-energy deuterons which must be examined in a background of protons which are usually much more intense. Since the interesting features of the angular distributions occur at small angles where interference with the direct beam is particularly bad, severe restrictions must be placed on the target material as to high-Z content. This is, however, somewhat compensated by the fact that the Q values for the (p,d) reactions on O^{16} and C^{12} are of considerably greater magnitude than for most other nuclei so that these materials may appear as target contaminants without interfering with the group being studied.

The relatively low proton beam intensity available precludes, in many cases, use of high-resolution magnetic analyzers and therefore the kind of detailed study frequently done on the (d,p) reaction. On the other hand, low-lying levels in light nuclei have, in many cases, separations of ~ 1 Mev which is considerably greater than the resolution of fairly simple detection systems such as the one employed here. It is also true that theoretical spectroscopy in light nuclei is still primarily concerned with the lower excitations so that even though fewer levels can be studied by (p,d) than by (d,p) the theoretical interest for a given nucleus is not greatly different.

II. EXPERIMENTAL METHODS

A. Counter Telescope

The incident proton energy used in the (p,d) experiments varied between 16.5 and 18.5 Mev. The cyclotron could be tuned and a beam extracted over this energy range giving protons of intensity adequate for experimentation. The large variation in Q values for (p,d) reactions—from a value slightly positive in the case of the $Be^9(p,d)Be^8$ ground-state reaction to about -12 Mev for the $N^{15}(p,d)N^{14}$ 2.31-Mev level reaction—made it necessary to detect deuterons ranging from about 6 to 16 Mev.

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Standing[1] and Reynolds and Standing[2] used a detection system utilizing a single NaI crystal. The crystal was cut as nearly as possible to the exact range of the deuteron group, and consequently protons of equal energy passed completely through, givings a maller light output. Therefore, the deuteron group appeared at a higher pulse height than any other group. Deuterons from a number of light elements were studied in this manner. Several difficulties were encountered and these were discussed by Standing. First, it was found to be quite difficult to cut crystals to the thickness desired (a few mil). What had to be done was to use crystals thinner than the deuteron range in conjunction with a variable absorber which lowered the energy of the group until it was exactly stopped. Also, if the crystals were not uniformly thick, a very sizeable spread in light output would result, depending upon where the deuterons traversed the crystal. Another difficulty which was encountered was the multiple scattering of some protons allowing them to traverse and stop in the crystal with an occasionally greater range than the crystal thickness. This was considered to be the cause of much of the observed background.

The experimental arrangement which was used in the present measurements is the familiar one frequently employed to separate particles of different charge and mass by a measurement of E and dE/dx simultaneously. The rate of energy lost together with E then classifies the type of particle. The dE/dx measurement can be accomplished by using a thin gas-filled proportional counter. For particles of identical charge (protons, deuterons, tritons), dE/dx is a function only of the velocity, and hence measurements of it and of E determine the mass unambiguously from the equation $M=2E/V^2$. It should also be noted that He^3 or He^4 with a charge twice that for protons or deuterons should have $dE/dx\sim16$ times greater for equal velocities and consequently will be easily distinguished. However, when a particle traverses a medium in which only a small fraction of its energy is lost to ionization, there is a statistical spread in energy loss which does not therefore allow a precise determination of velocity and hence of mass. The problem encountered in resolving protons and deuterons of equal energy then resolves itself into determining whether or not the spread is large enough to allow a significant number of protons to be interpreted as deuterons, all other particles presumably being easily recognized.

The amount of ionization per unit track length varies partly because the number of collisions is governed by Poisson's law and partly because the energy transferred at each collision varies. Early[3] treatments of the problem showed that the fluctuation curve (variation in energy loss for identical particles traversing a given amount of material and losing only a small amount of energy) could be roughly explained by a Gaussian due to the majority of events which are of the low-energy transfer variety plus a broad tail falling off approximately as $1/E^2$ where E is the energy loss of the particle. The $1/E^2$ tail was considered to be due to occasional events which transferred an unusually large amount of energy to the electron. Symon[4] carried out more detailed calculations on this distribution and reported results which are in good agreement with experiment. On the basis of Symon's work, proton and deuteron ionization loss distributions for thin gas-filled counters were computed in an attempt to determine whether or not the broad high-energy tail characteristic of the process from protons would interfere appreciably with the deuterons of equal energy but having a greater mean energy loss. In a sample calculation in which particles (protons and deuterons of 5 Mev) were assumed to pass through $1\frac{1}{2}$ in. of argon at STP the proton tail was not great enough to present a subtraction difficulty even though deuterons were considerably less intense. The full width at $\frac{1}{2}$ maximum of the distribution is only about 30 kev for both distributions with the protons losing 160 kev and the deuterons 260 kev on the average.

Igo and Eisberg[5] suggested that the resolution of the proton and deuteron groups could be improved using several thin gas counters in a telescope arrangement, and this device was employed by Ribe[6] in studying the (n,d) reaction on F^{19}. In this method the smallest of several pulses from a series of identical thin counters is chosen to characterize the event. The distribution from each counter will present the characteristic shape involving the broad Landau tail. The low-energy end of the distribution rises quite rapidly, and therefore the smallest of several pulses created by the same ionizing particle might be expected to lie in this low-energy region and not vary as much as for a single event. Calculations were done based on Symon's thesis in which the method of Igo and Eisberg was compared for resolution with that which would have resulted using a single counter having the same total ionizing path. For sufficiently thin velocity selectors, the former method does indeed improve resolution. However, the advantage over a single equivalent counter disappears when energy loss of the charged particle is of the order of 100 kev or more. The completed velocity selector was checked with deuteron and proton groups of known energy and distributions agreed very well with those calculated.

The actual construction of the proportional counter was dictated by a number of considerations. First, it was necessary to have the particles lose sufficient energy in the counter so that good resolution of the proton and deuteron groups could be obtained even for proton intensities many times that of the deuterons. Because

[1] K. G. Standing, Phys. Rev. **101**, 152 (1956).
[2] J. B. Reynolds and K. G. Standing, Phys. Rev. **101**, 158 (1956).
[3] E. J. Williams, Proc. Roy Soc. (London) **125**, 420 (1929).
[4] K. Symon, Ph.D. thesis, Harvard, 1948 (unpublished).
[5] G. Igo and R. M. Eisberg, Rev. Sci. Instr. **25**, 450 (1950).
[6] F. L. Ribe, Phys. Rev. **106**, 767 (1957).

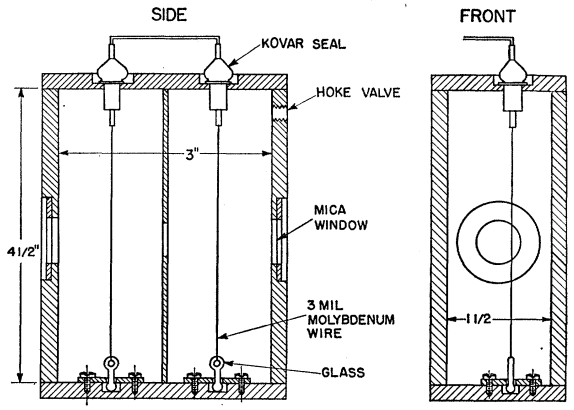

FIG. 1. Proportional counter used as a velocity selector.

of the wide range of deuteron energies encountered, a counter which would operate over a wide range of gas pressures was desired. Argon commercially mixed with 4% CO_2 was used as a filling gas. Estimates of the amount of gas needed for adequate particle resolution of the most energetic deuterons led to a path length in the counter of about 3 in. assuming a pressure of 1 atmosphere. The size of the center collecting wire was determined chiefly by considerations of gas amplification and the desire to keep transit times short. Since it was intended to use the counter in a coincidence arrangement with resolving times as short as possible, a narrow-diameter collecting wire and high gas multiplication were essential. To keep transit time short, reasonably intense fields across the counter had to be maintained. A compromise between these numerous considerations led to use of a center wire of 3-mils diameter and an operating voltage (determined experimentally) of about 1600 volts depending upon pressure. The counter (Fig. 1) had two identical sections $1\frac{1}{2}$ in. square and $4\frac{1}{2}$ in. long. This was considered to be an improvement over a single counter with a 3-in. path from considerations of field uniformity and intensity at a distance from the center wire. The division between the two sections was by means of a $\frac{1}{32}$-in. brass plate with a hole just adequate to pass the beam. The center wires were attached at one end with glass hooks and were led through a Kovar seal at the other. The counter was silver soldered except at one side which, to avoid further heating after electrodes and mica windows were in place, was attached with epoxy resin. Thin ($\sim$2 mg/cm^2) mica windows were found to be more suitable than organic materials. Window mounts were constructed in the manner described by Standing.[1] The counter showed no apparent deterioration over intervals of several months.

Collimation was done at the entrance to the proportional counter. The beam in traversing the counter was spread somewhat due to multiple scattering, but calculations showed that for the window geometries and collimators employed there was negligible loss due to scattering from the effective counting area. Experimental tests which were conducted confirmed these calculations.

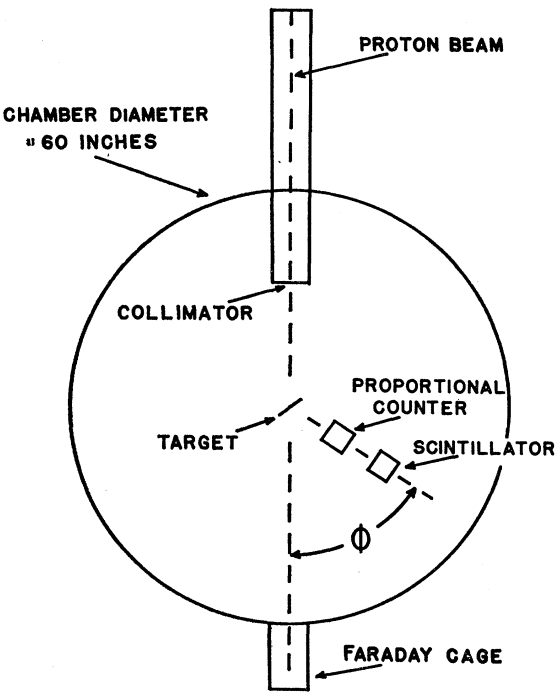

FIG. 2. Top view of 60-inch scattering chamber.

A thin ($\frac{1}{8}$ in.) NaI crystal was used to stop all charged particles which traversed the velocity selector. The resolution of this energy detector for the incident proton beam was about 2%.

Two 6AK5 pentodes in parallel and connected as triodes served in each preamplifier unit. The counters and preamplifiers were used in vacuum in the scattering chamber.

B. Procedures

All distributions were taken in the 60-in. scattering chamber described by Yntema and White[7] (see Fig. 2). The beam was collimated at the entrance to the chamber by a $\frac{1}{4}$-in. hole. This gave a beam spot $\frac{3}{8}$ in. diameter at the target. After passing through the target, undeflected protons were collected in a Faraday cage. The charge collected was used to normalize the data at different angles and compute absolute cross sections. Since most targets were not uniform, a monitor counter at $\sim$20° to the beam was used in conjunction with the Faraday cage. A correspondence between deuteron counts and monitor counts would then be maintained even though beam intensity varied with time over different parts of the foil. Actually, some inserted material (usually polyethylene) binder was ordinarily present in addition to the target material, but this was always quite thin and uniform and could be allowed for.

[7] J. L. Yntema and M. G. White, Princeton University Technical Report NYO-3478, May 15, 1952 (unpublished).

Energy calibration and stability of the proton beam were checked frequently using an end-point ionization detector described by Schrank.[8] Absorbers were used to slow some protons, deflected by a few degrees in the target, to an energy such that they could be completely stopped between two identical sections of an ion counter. Whether the proton energy is high or low is indicated by a difference in current in the two sections of the counter. The beam could then be set to any given energy with an accuracy of about 20 kev by inserting the appropriate absorber and adjusting the cyclotron magnetic field. During an experiment the beam energy could be quickly checked and the cyclotron readjusted if a drift was detected. After a 2-hour warm-up period the cyclotron was found to be stable to about 50 kev, but for quickly obtaining a beam of accurately known energy, the device proved of great value.

The procedure in obtaining the $C^{13}(p,d)C^{12}$ and $P^{31}(p,d)P^{30}$ distributions was as follows. Pulses from the NaI detector were amplified and fed into a single-channel discriminator, the output of which was used to generate a gating signal for a 20-channel pulse-height analyzer. In this manner the velocity spectrum of charged particles as measured by the dE/dx detector could be viewed in coincidence with an arbitrary interval of particle energy as indicated by the NaI crystal. If deuterons were present, a double peak would be observed with deuterons appearing at twice the pulse-height of the proton background. A search for deuterons could be carried out at a fixed laboratory angle by recording dE/dx spectra for successive energy intervals. When a deuteron group appeared, the proportional counter pulses were fed to a single-channel discriminator with window set to enclose the deuteron group. The discriminator signal was used to gate the 20-channel analyzer and the coincident NaI crystal spectrum was observed. This resulted in a double grouping of events, those at greatest pulse height being interpreted as of deuteron origin and free from proton contamination. The energy spectrum in the NaI detector could, in this manner, be cleared of proton contamination for each angle, and individual groups which appeared were then integrated.

For a consistency check, each angular distribution was repeated and if the separate runs were within estimated errors, the sum of counts for both runs was taken. In cases where agreement was poor, repeat checks were made and the source of the difficulty ascertained. Except in a few cases where interference from very intense proton background was encountered, the only significant source of error was in counting statistics.

Most of the work on the remaining experiments was done using a 100-channel two-dimensional pulse-height analyzer.[9] This instrument took pulses directly from the counters and recorded the height of each coincidence pulse on tape. Having recorded all data, it was then possible to analyze the results by viewing either spectrum in coincidence with any given region of the other according to the procedure outlined in the preceding paragraph. The advantage of this instrument was that all of the deuteron groups from a reaction at a given angle could be studied simultaneously. A considerable amount of data could be accumulated during the scheduled running time and analyzed at leisure without interfering with other experiments.

III. ANGULAR DISTRIBUTIONS

The data to be presented in this report are included in the summary of stripping reactions which has been carried out recently by Macfarlane and French.[10] These authors are entirely concerned with the spectroscopic significance of the level widths and level width ratios which may be extracted from angular distributions in stripping (or pickup) reactions using the original version of the Butler theory. The notation of Macfarlane and French will be adhered to in the following discussion of experimental results, and the reader is referred to this reference for nuclear model analysis of level widths.

The procedure followed in analyzing data was to consider r_0, the nuclear radius, an adjustable parameter and to calculate Butler curves for intervals of about 0.2 fermi, taking finally that curve which gave the best visual fit to the data. The choice of the neutron angular momentum l could, in almost every case, be made unambiguously by inspection of the experimental distribution.

The lowest Z target material employed in this series of measurements was Li^7. These results have been reported previously.[11]

$C^{13}(p,d)C^{12}$ ($E=17.0$ Mev)

Carbon enriched to 60% in C^{13} in the form of $BaCO_3$ was obtained from Eastman Kodak Company. The barium and oxygen contamination contribute intense proton background which would have made resolution of the deuteron and proton groups difficult and so it was thought advisable to remove these elements. To accomplish this a technique described by Bromley[12] and used in C^{14} dating was made use of. First, the $BaCO_3$ sample was mixed with an equivalent of $PbCl_2$ and dissolved in a solution of 60% $NaNO_3$ and 40% KNO_3 at 360°C. The reaction of interest is

$$BaCO_3+PbCl_2 \rightarrow PbO+BaCl_2+CO_2.$$

The CO_2 was led into a quartz reaction tube which could be maintained at 800°C. The tube contained a quartz boat which was charged with Mg turnings and a

[8] G. Schrank, Rev. Sci. Instr. **26**, 677 (1955).
[9] M. Birks, T. Braid, and R. Detenbeck, Rev. Sci. Instr. **29**, 203 (1958).
[10] M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).
[11] E. Bennett and D. Maxson, Phys. Rev. **116**, 131 (1959).
[12] D. A. Bromley, Phys. Rev. **88**, 565 (1952).

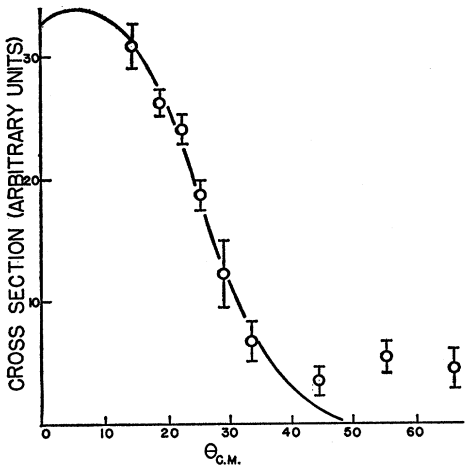

FIG. 3. Angular distribution of deuterons from the reaction $C^{13}(p,d)C^{12}$ leaving C^{12} in the ground state. Errors shown refer to relative values. $E=17.0$, $l=1$, and $r_0=4.2\times10^{-13}$ cm.

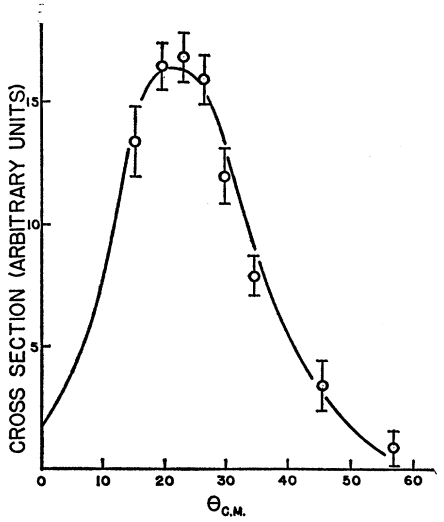

FIG. 4. Angular distribution of deuterons from the reaction $C^{13}(p,d)C^{12}$ leaving C^{12} in an excitation of 4.43 Mev. Errors shown refer to relative values. $E=17.0$ Mev, $l=1$, and $r_0=4.2\times10^{-13}$ cm.

few grams of Cd as a catalyst. The CO_2 was reduced by Mg and elemental carbon deposited in a sooty black layer over the Mg. After the reaction had gone to completion the contents of the boat (C, Mg, MgO, Cd, traces of $BaCO_3$, BaO) was dumped into a beaker of hot concentrated hydrochloric acid. All of these compounds went into solution except elemental carbon. After filtering and washing, the residue of 40% C^{12} and 60% C^{13} was mixed with a small amount of polystyrene in benzene and spread out by mechanical agitation over a glass plate. When the benzene had evaporated, it was possible to remove the foil with a thin razor blade. The foil used was estimated to be 3 mg/cm^2 thick and to be 1.0 mg/cm^2 of C^{13}.

The experimental angular distributions of deuterons leaving C^{12} in an excitation of 0 and 4.43 Mev are shown in Figs. 3 and 4. The wide level spacing in the C^{12} nucleus (second excited state at 7.65 Mev) permitted angular distributions for each state to be taken without fear of interference from the others. The $C^{12}(p,d)C^{11}$ is too endothermic to permit deuterons from this reaction to be seen. The Butler curves are for $l=1$ and $r_0=4.2\times10^{-13}$ cm, and were considered the best visual fit to the data. The value of r_0, although somewhat less than would be expected from similar experiments on neighboring nuclei, is in agreement with results of deuteron stripping on C^{12} carried out by many investigators. The $l=1$ assignment for both distributions is in agreement with the known spins of $\frac{1}{2}^-$ for the C^{13} ground state and 0^+ and 2^+ for the two lowest states of C^{12}. Experimental errors are in counting statistics. The absolute cross section for the (p,d) reaction leading to the ground state of C^{12} at a center-of-mass angle of 21° was estimated to be ~5 mb/steradian, a value which is about a factor of three less than would be indicated by the corresponding stripping reaction. This is perhaps not surprising since the manner in which the target was constructed made an estimate of its thickness quite difficult. The ratio of the product of the spectroscopic factor S and the isotopic spin coupling factor $I=[C_{t_0\frac{1}{2}t}{}^{T_0\frac{1}{2}T}]^2$ (the product SI is proportional to the reduced level width between the target and the residual nucleus[10]) was measured to be

$$\frac{S^*I^*[C^{13}(p,d)C^{12}\ 4.43\ \text{Mev}]}{SI[C^{13}(p,d)C^{12}\ \text{ground state}]}=0.97.$$

It is convenient to list the ratio of the product of S and I since it is this product which is measured directly in a (p,d) pickup experiment.

The Hamiltonian corresponding to the ground state of C^{13} and to the two lowest levels in C^{12} was constructed according to the intermediate-coupling shell model. These matrices were diagonalized and wave functions obtained for these levels as a function of the intermediate coupling strength parameter a/k. Spectroscopic ratios S^*/S (I and I^* are unity) were calculated and are shown plotted against $(a/k)/(a/k+6)$ in Fig. 5. The experimental value is also shown and it is clear that a value of a/k well into the j-j coupling limit $(a/k\rightarrow\infty)$ is required to give rough agreement with the observed ratio.

$N^{14}(p,d)N^{13}$ ($E=1.85$ Mev)

N^{14} was obtained in the form of melamine as a finely divided powder. By mixing melamine in a solution of benzene in polystyrene and shaking, a homogeneous milky emulsion was formed which was then poured onto a clean glass plate tilted at 45°. A thin film of the mixture would cling to the glass surface and when dry, foils of about 2-mg/cm^2 thickness could be removed

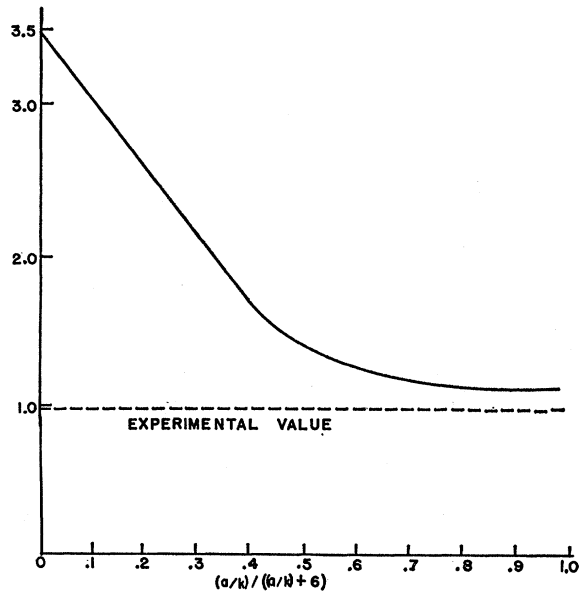

FIG. 5. Level width ratio vs intermediate coupling for $C^{13}(p,d)C^{12}$.

after soaking in water.[13] The foils appeared quite uniform and worked satisfactorily. Carbon and oxygen contamination is not harmful in small amounts since any deuterons from (p,d) reactions on C^{12} and O^{16} will be at too low an energy to interfere.

Again we were confronted with a rather favorable situation experimentally in observing deuterons from the reaction $N^{14}(p,d)N^{13}$, in that low-lying states in N^{13} are well spaced. The ground state of N^{13} is known to be $\frac{1}{2}^-$. There is a $J^\pi=\frac{1}{2}^+$ state at 2.37 Mev and a doublet at about 3.5 Mev with $J^\pi=\frac{3}{2}^-$ and $\frac{5}{2}^+$. A deuteron spectrum taken at 16° lab system is shown in Fig. 6. The $N^{14}(p,d)N^{13}$ ground-state distribution has been studied by Standing[1] and we reproduce his results in Fig. 7 together with distributions for the 2.37-Mev state and the states at 3.5 Mev. Enough data on the ground state were taken to permit normalization to Standing's data. The deuteron group leaving N^{13} in an excitation of 2.37 Mev, though weak, was well resolved from the 3.5-Mev group and could be studied. Error flags indicate probable error in counting although there was some difficulty in resolving deuterons to the 2.37-Mev state from the proton background, with the consequence that these data are probably not very reliable.

The $l=0$ assignment to the 2.37-Mev group appears to be reasonable. Any $l=2$ admixture in the distribution must certainly be small. The observed s-wave pickup is in agreement with the known spin of 1^+ for N^{14} and $\frac{1}{2}^+$ for the 2.37-Mev state in N^{13}.

The distribution of deuterons to the state (or states) at about 3.5 Mev can be fit fairly well, in the forward direction at least, by $l=1$ and $r_0=5.0\times10^{-13}$ cm. Since there is an even-parity level within about 50 kev of the known $\frac{3}{2}^-$ state, the experimental distribution will be a sum of contributions from both of these. The cross section actually does seem somewhat larger at back angles than would be consistent with $l=1$ alone, however the Butler theory is usually incapable of fitting data except in the forward direction, and even if more accurate data were available it is unlikely that the presence of an $l=2$ component [which is required by the (p,d) pickup reaction to the $\frac{5}{2}^+$, 3.56-Mev state in N^{13}] could be definitely established. For the ratio of the product of S and I we find

$$\frac{S^*I^*[N^{14}(p,d)N^{13}\ 2.37\ \text{Mev}]}{SI[N^{14}(p,d)N^{13}\ \text{ground}]}=0.06,$$

$$\frac{S^*I^*[N^{14}(p,d)N^{13}\ 3.51\ \text{Mev}]}{SI[N^{14}(p,d)N^{13}\ \text{ground}]}=0.38.$$

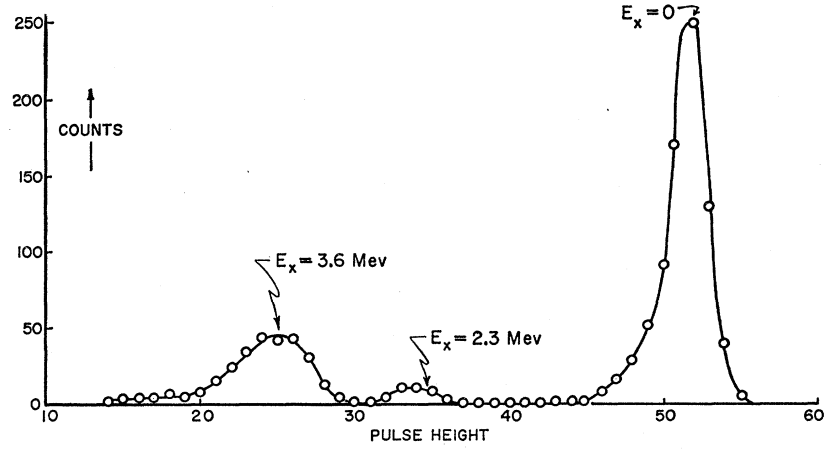

FIG. 6. Scintillator spectrum of deuterons from the reaction $N^{14}(p,d)N^{13}$. The laboratory angle is 16°.

[13] This technique for preparing melamine foils was communicated to the author by Dr. R. Detenbeck.

Auerbach and French[14] have carried out intermediate-coupling calculations for the (p,d) reaction leading to the ground and 3.51-Mev state in N^{13}, and in Fig. 8 we reproduce these results, together with the experimentally observed ratio.

The significance of a finite cross section for the $N^{14}(p,d)N^{13}$ 2.31-Mev reaction has been discussed by Standing[1] and by Macfarlane and French.[10] Briefly, any s-wave or d-wave pickup on N^{14} indicates a departure from the usual shell-model assumption concerning the ground state of N^{14}, namely, that it is pure p^{10} and consequently neutron pickup should lead only to pure p^9 configurations in N^{13}. However, if higher s and d configurations are present in the N^{14} ground state, then breakup such as $p^{10} \rightarrow p^8 s^2$, and $p^{10} \rightarrow p^8 sd$ are permitted and it would then be possible to pick off s and d neutrons. The magnitude of this cross section then allows a direct estimate to be made of the purity of the N^{14} ground-state wave function.

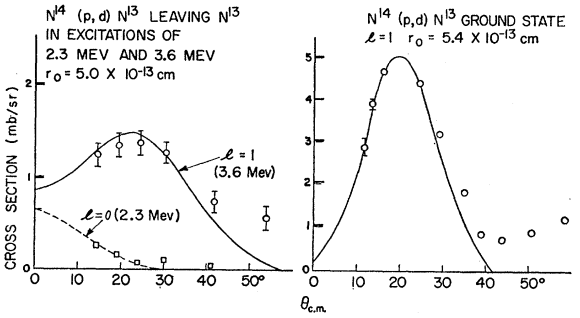

FIG. 7. Angular distribution of deuterons from the reaction $N^{14}(p,d)N^{13}$. The incident proton energy is 18.5 Mev. Errors shown refer to relative values.

$N^{15}(p,d)N^{14}$ ($E = 18.6$ Mev)

A nitrogen target was prepared from ammonium nitrate[15] enriched to about 95% in N^{15}. A sample of the nitrate was dissolved in water and the solution evaporated to dryness on a glass plate. A small amount of benzene in polystyrene was spread over the salt and the whole complex lifted from the plate with a thin razor blade. Foils of ~ 4 mg/cm^2 thickness with about 1.2 mg/cm^2 of N^{15} could be prepared in this manner.

Deuterons leaving N^{14} in an excitation of 0, 2.31, and 3.95 Mev were observed (Figs. 9, 10, 11, and 12). The large separation of these states permitted deuterons to these levels to be studied without fear of overlapping. Counting statistics are then the only source of experimental error in these distributions. The deuteron group corresponding to the 3.95-Mev level in N^{14}, though well separated from the 2.31-Mev group, was not entirely resolved from a rather more intense deuteron group at

[14] T. Auerbach and J. B. French, Rochester University Technical Report NYO-3478, 1952 (unpublished).

[15] Isomet Corporation, 118 Union Street, Palisades Park, New Jersey.

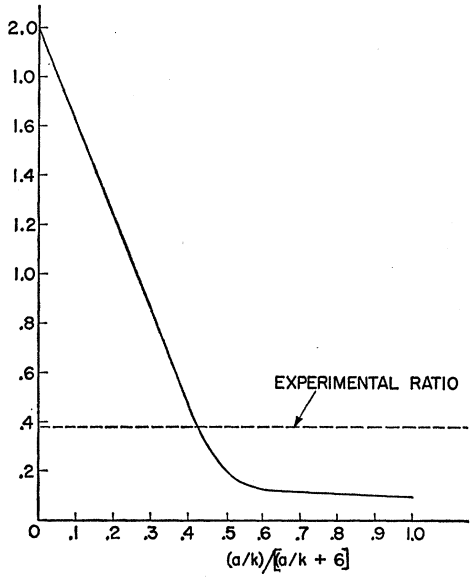

FIG. 8. Level width ratio vs intermediate coupling for $N^{14}(p,d)N^{13}$.

lower energy which has a Q value appropriate to the $O^{16}(p,d)O^{15}$ reaction (oxygen being present in the target). The error flags for this state then include an estimate of uncertainty in resolving it from deuteron contamination, and consequently the data appear less reliable than for the 2.31-Mev state which is roughly comparable in intensity.

The data to the ground state and the 2.31-Mev state are fit quite nicely assuming $l=1$ and $r_0 = 5.4 \times 10^{-13}$ cm. The data on the 3.95-Mev state are much less con-

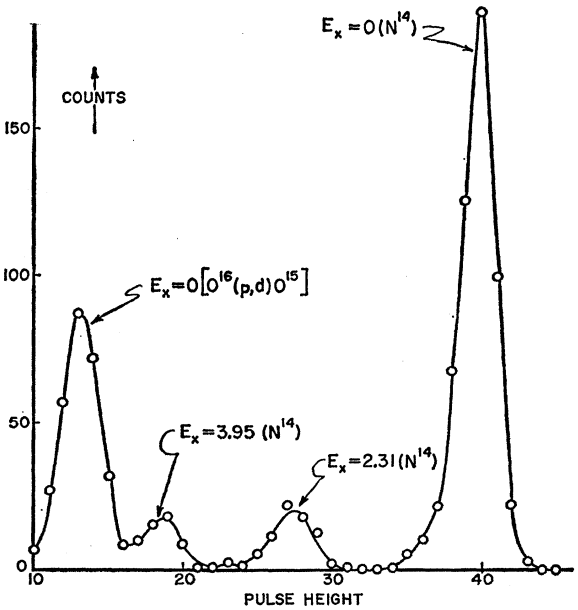

FIG. 9. Scintillator spectrum of deuterons from the reaction $N^{15}(p,d)N^{14}$ at 16° in the laboratory system.

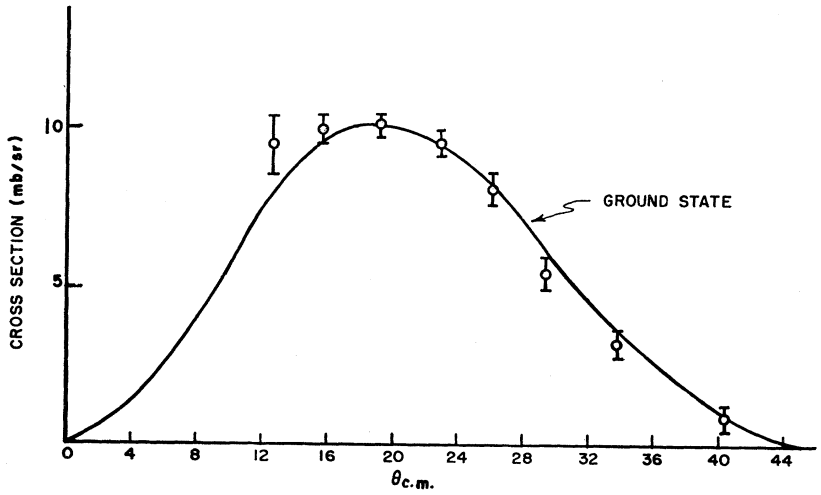

FIG. 10. Angular distribution of deuterons from the reaction $N^{15}(p,d)N^{14}$ leaving N^{14} in the ground state. Errors shown refer to relative values. $E=18.6$ Mev, $l=1$, and $r_0=5.4\times10^{-13}$ cm.

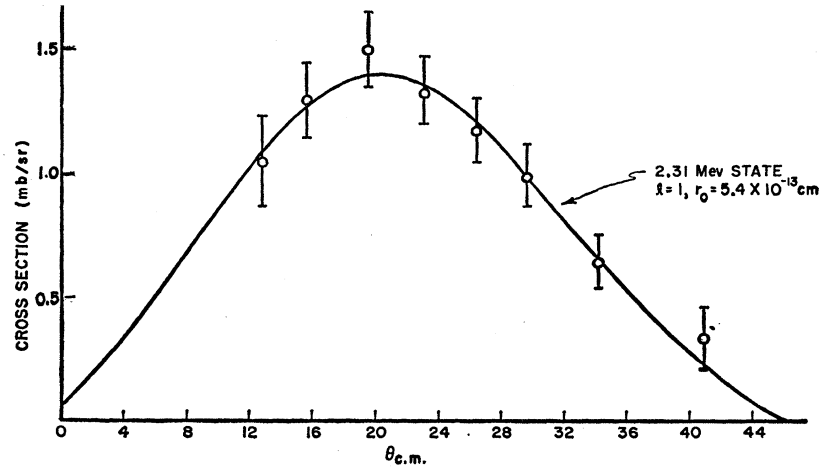

FIG. 11. Angular distribution of deuterons from the reaction $N^{15}(p,d)N^{14}$ leaving N^{14} in an excitation of 2.31 Mev. Errors shown refer to relative values. $E=18.6$ Mev.

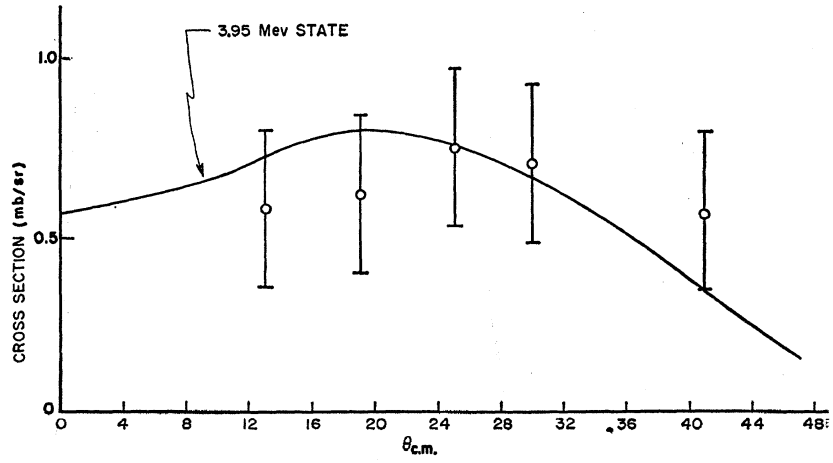

FIG. 12. Angular distribution of deuterons from the reaction $N^{15}(p,d)N^{14}$ leaving N^{14} in an excitation of 3.95 Mev. Errors shown refer to relative values. $E=18.6$ Mev, $l=1$, and $r_0=4.8\times10^{-13}$ cm.

vincing, however, and though the $l=1$, $r_0=4.8\times10^{-13}$ cm parameters are not in disagreement with experimental results, an $l=2$ assignment and some other radius will do just as well. However, the level at 3.95 Mev is well established as 1^+ and this value could only result from p-wave pickup on N^{15}. The ground state and the 2.31-Mev state of N^{14} are known to be 1^+ and 0^+, respectively, in agreement with the observed p-wave pickup.

The target material used contained about 6% of N^{14}

and since the Q values for $N^{14}(p,d)N^{13}$ and $N^{15}(p,d)N^{14}$ are almost identical, the deuteron group to the ground state of N^{14} is slightly contaminated. However, the contamination can be estimated to sufficient accuracy since the cross sections for both of these reactions are approximately known.

Stripping ratios were found to be

$$\frac{S^*I^*[N^{15}(p,d)N^{14}\ 2.31\ \text{Mev}]}{SI[N^{15}(p,d)N^{14}\ \text{ground}]}=0.23,$$

$$\frac{S^*I^*[N^{15}(p,d)N^{14}\ 3.95\ \text{Mev}]}{SI[N^{15}(p,d)N^{14}\ \text{ground}]}=0.17.$$

The experiment was repeated for a few forward angles after reducing the incident proton energy from 18.5 Mev to 17.0 Mev. The ratio of cross sections for the 2.31-Mev state to the ground state was found to be essentially the same at the maximum of the distributions.

The region of the $1p$ shell near mass number 14 has received an unusual amount of attention both experimentally and theoretically. Except for stripping and pickup data these results are summarized by Sherr *et al.*[16] The reader is referred to Macfarlane and French[10] for a discussion of the significance of the (p,d) pickup results on shell-model wave functions for these nuclei.

$F^{19}(p,d)F^{18}$ ($E=18.5$ Mev)

The target material used in this experiment was $\frac{1}{4}$-mil Teflon. Foils were obtained commercially and were 1.37 mg/cm^2 thick.

The only previous work on F^{19} was done by Reynolds[2] who studied the deuteron group leaving F^{18} in its ground state. Typical deuteron spectra are recorded in Figs. 13 and 14. Well-defined states appear at an excitation of 0, 1.0, 1.7, 3.4, and 4.1 Mev. Deuterons were also observed corresponding to an excitation

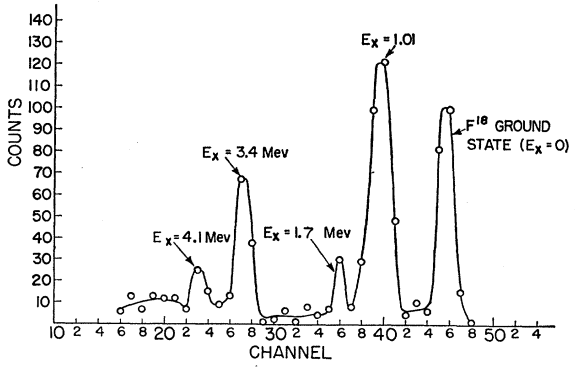

FIG. 13. Scintillator spectrum of deuterons from the reaction $F^{19}(p,d)F^{18}$ at 18° in the laboratory system.

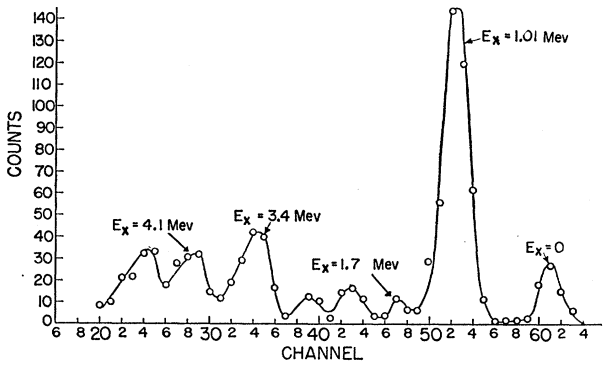

FIG. 14. Scintillator spectrum of deuterons from the reaction $F^{19}(p,d)F^{18}$ at 50° in the laboratory system.

between 2 and 3 Mev, but were too weak to study. As can be seen, data on the group at ~4.1 Mev presented a background subtraction problem as did, to a lesser extent, data on the 1.7-Mev state. The error flags for these distributions contain an estimate of error due to this subtraction.

The distribution to the ground state of F^{18} is given in Fig. 15. It is a very clean case of s-wave pickup, in agreement with the results of Reynolds and with the assignment of $J^\pi=\frac{1}{2}^+$ for the F^{19} ground state and 1^+ for the F^{18} ground state. No d-wave component is indicated, the experimental distribution falling to zero at 28°. The radius required to best fit the data was 6.0×10^{-13} cm, a value slightly larger than might be expected for this nucleus.

The distribution of deuterons leaving F^{18} in an excitation of about 1 Mev is recorded in Fig. 16. Clearly, s-wave pickup is again indicated; however, a hump occurs in the distribution at about 30°. Also, data at back angles seem to indicate a rather isotropic background. The best fit was obtained by superimposing s-wave pickup with a radius of 6.0×10^{-13} cm and d-wave pickup with $r_0=5.2\times10^{-13}$ cm. The ratio of level widths

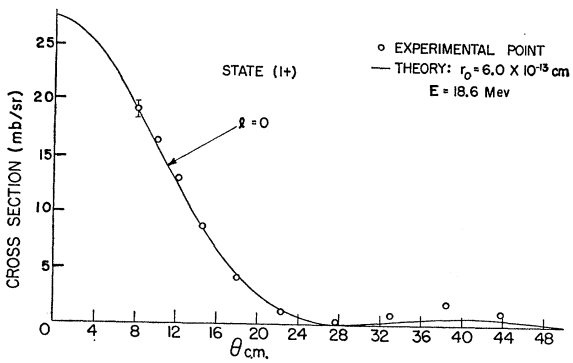

FIG. 15. Angular distribution of deuterons from the reaction $F^{19}(p,d)F^{18}$ leaving F^{18} in the ground state. Errors shown refer to relative values.

[16] R. Sherr, J. B. Gerhart, H. Horie, and W. F. Hornyak, Phys. Rev. **100**, 945 (1955).

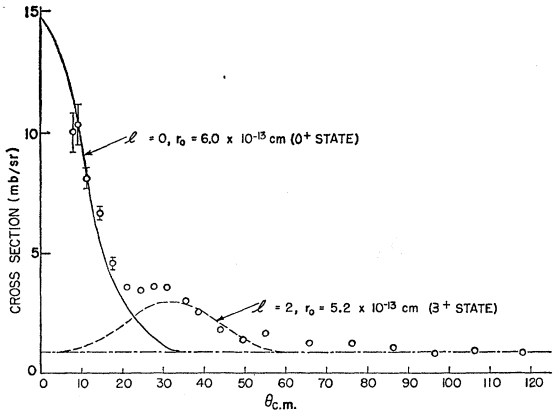

FIG. 16. Angular distribution of deuterons from the reaction $F^{19}(p,d)F^{18}$ leaving F^{18} in an excitation of 1.0 Mev. Errors shown refer to relative values.

for these states was found to be

$$\frac{S^*I^*[F^{19}(p,d)F^{18}\ 1\ \text{Mev},\ d\text{-wave}]}{SI[F^{19}(p,d)F^{18}\ \text{ground}}=1.5,$$

$$\frac{S^*I^*[F^{19}(p,d)F^{18}\ 1\ \text{Mev},\ s\text{-wave}]}{SI[F^{19}(p,d)F^{18}\ \text{ground}}=0.45.$$

There exists clear indication of a quartet of states in F^{18} at about 1 Mev and within the resolution of this experiment. The J^π assignments for the 0.914 and 1.129-Mev states are known to be 3^+ and 5^+, respectively. Two other levels are known to exist at 1.042 and and 1.087 Mev and these are believed to be spin zero but of opposite parity. The experimental level widths reported here for s-wave and d-wave pick-up are consistent with the $J=0^+$, $T=1$ and $J=3^+$, $T=0$ levels in this quartet.[10] The presence of some $l=1$ contribution to the $J=0^-$ level cannot be ruled out, however.

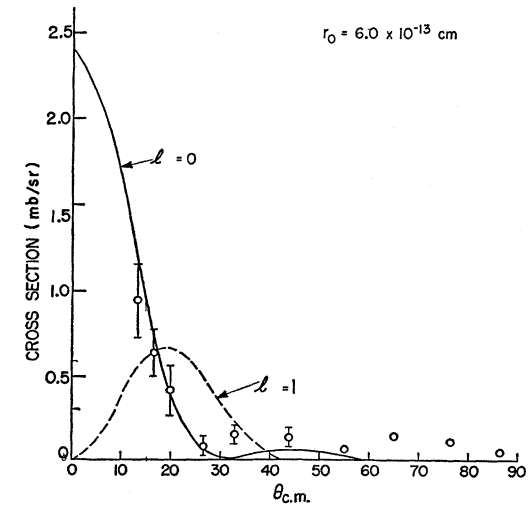

FIG. 17. Angular distribution of deuterons from the reaction $F^{19}(p,d)F^{18}$ leaving F^{18} in an excitation of 1.7 Mev. Errors shown refer to relative values.

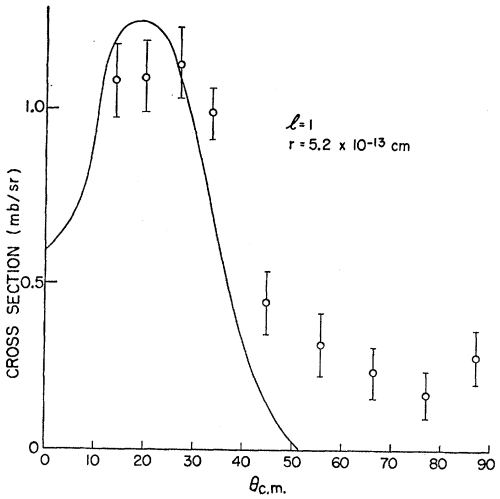

FIG. 18. Angular distribution of deuterons from the reaction $F^{19}(p,d)F^{18}$ leaving F^{18} in an excitation of 3.4 Mev. Errors shown refer to relative values.

In Fig. 17 we show the distribution taken for the group leaving F^{18} in an excitation of 1.7 Mev. The $l=0$ assignment is clearly indicated and the level width ratio is

$$\frac{S^*I^*[F^{19}(p,d)F^{18}\ 1.7\ \text{Mev}]}{SI[F^{19}(p,d)F^{18}\ \text{ground}]}=0.08.$$

The distribution for the state at 3.4 Mev is shown next in Fig. 18. The Butler curve is for $l=1$ and $r_0=5.2\times10^{-13}$ cm, and although the fit at large angles is not good, no other l assignment will do as well.

In Fig. 19 we give the distribution of the state at highest excitation in F^{18} which could be studied (4.1 Mev). The large error flags are the result of rather uncertain background subtractions as well as counting

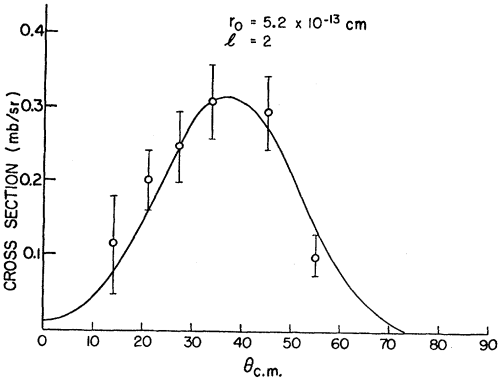

FIG. 19. Angular distribution of deuterons from the reaction $F^{19}(p,d)F^{18}$ leaving F^{18} in an excitation of 4.1 Mev. Errors shown refer to relative values.

statistics. A Butler curve with $r_0=5.2\times10^{-13}$ cm and $l=2$ gives a good fit to the data. We find for this level width ratio

$$\frac{S^*I^*[F^{19}(p,d)F^{18}\ 4.1\ \text{Mev}]}{SI[F^{19}(p,d)F^{18}\ \text{ground}]}=0.5.$$

$Mg^{25}(p,d)Mg^{24}$ ($E=17.0$ Mev)

MgO enriched to 90% in the Mg^{25} isotope was obtained from Oak Ridge National Laboratory. It was found possible to mix the oxide in a sludge with benzene and polystyrene. The sludge could then be spread over a glass plate and after the benzene evaporated, a foil ~4 mg/cm^2 could be picked off with a thin razor blade. The foil contaminants (O^{16}, C^{12}, Mg^{24}) all have (p,d) Q values of sufficient magnitude so that they do not contribute deuteron groups which interfere with those from the $Mg^{25}(p,d)Mg^{24}$ reaction.

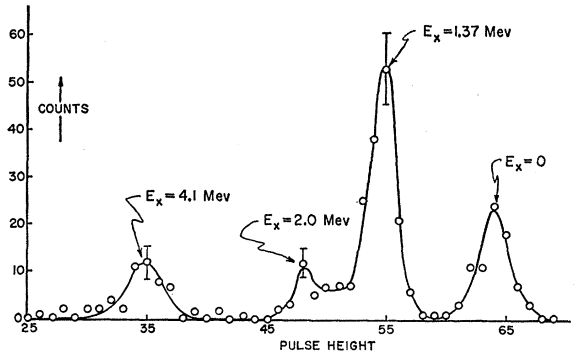

FIG. 20. Scintillator spectrum of deuterons from the reaction $Mg^{25}(p,d)Mg^{24}$ at 30° in the laboratory system.

An energy spectrum of deuterons from this reaction is shown in Fig. 20. In Figs. 21 and 22 we present the experimental distributions of deuterons leaving Mg^{24} in an excitation of 0, 1.37, and 4.1 Mev. An angular momentum transfer of $l=2$ and a radius of 5.2×10^{-13} cm gives a good fit to the data. The anomalous background which appears in Fig. 20 at ~2 Mev was not reproduced at other angles and may have been due to interference from a strong inelastic proton group. The $l=2$ value for the ground state is consistent with the known assignments of $\frac{5}{2}^+$ for Mg^{25} and 0^+ for Mg^{24}. The 1.37-Mev state in Mg^{24} is known to be 2^+ and this is also consistent with the $l=2$ found experimentally. The known doublet at ~4.1 Mev could not be resolved, and both levels (4^+, 2^+) may be reached by d-wave pickup on Mg^{25}. It is also interesting to note that $l=0$ pickup to the 1.37-Mev state, though permitted by selection rules, does not occur as can be seen from inspection of Fig. 21. Usually the lower l values are strongly favored by the stripping mechanism where selection rules

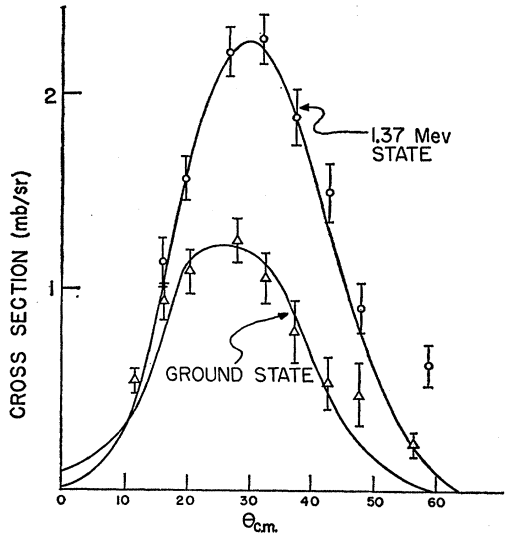

FIG. 21. Angular distribution of deuterons from the reaction $Mg^{25}(p,d)Mg^{24}$ leaving Mg^{24} in an excitation of 0 and 1.37 Mev. Errors shown refer to relative values. $r_0=5.2\times10^{-13}$ cm, $l=2$, and $E=17.0$ Mev.

permit several l values to compete. Stripping ratios are

$$\frac{S^*I^*[Mg^{25}(p,d)Mg^{24}\ 1.37\ \text{Mev}]}{SI[Mg^{25}(p,d)Mg^{24}\ \text{ground}]}=2.2,$$

$$\frac{S^*I^*[Mg^{25}(p,d)Mg^{24}\ 4.1\ \text{Mev}]}{SI[Mg^{25}(p,d)Mg^{24}\ \text{ground}]}=0.65.$$

$P^{31}(p,d)P^{30}$ ($E=18.6$ Mev)

A foil suitably thin for (p,d) experimentation was prepared by mixing powdered phosphorous with ben-

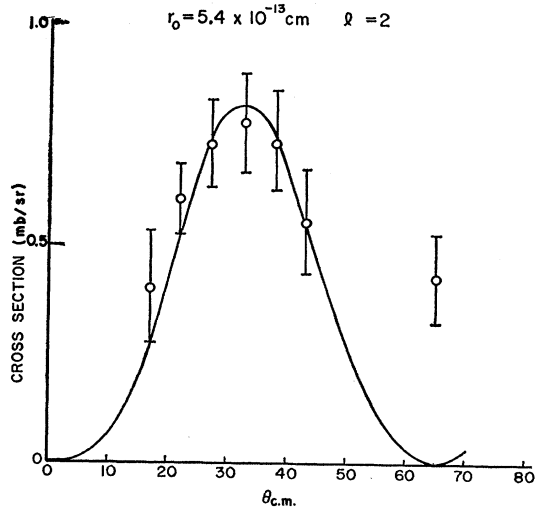

FIG. 22. Angular distribution of deuterons from the reaction $Mg^{25}(p,d)Mg^{24}$ leaving Mg^{24} in an excitation of 4.1 Mev. Errors shown refer to relative values.

TABLE I. Summary of (p,d) pickup experiments.

Reaction	Proton lab energy (Mev)	Excitation of residual nucleus (Mev)	Angle (deg) c.m. system	Neutron orbital l	Radius (fermis)	Level width ratio S^*I^*/SI
$C^{13}(p,d)C^{12}$	17.0	0	21	1	4.2	1
		4.43	21	1	4.2	0.97
$N^{14}(p,d)N^{13}$	18.5	0	20	1	5.4	1
		2.37	15	0?	5.0	0.06
		3.6	20	1	5.0	0.38
$N^{15}(p,d)N^{14}$	18.6	0	20	1	5.4	1
		2.31	20	1	5.4	0.23
		3.95	20	1?	4.8	0.17
$F^{19}(p,d)F^{18}$	18.5	0	10	0	6.0	1
		1.0	33	2?	5.2	1.5
		1.0	12	0	6.0	0.45
		1.7	15	0	6.0	0.08
		3.4	20	1	5.2	...
		4.1	40	2?	5.2	0.5
$Mg^{25}(p,d)Mg^{24}$	17.0	0	28	2	5.2	1
		1.37	28	2	5.2	2.2
		4.1	33	2	5.2	0.65
$P^{31}(p,d)P^{30}$	18.6	0	12	0	5.6	1
		0.8	12	0	5.6	0.75

zene and polystyrene as a binder. When the mixture was poured onto a glass plate and the benzene permitted to evaporate, foils ~ 3 mg/cm^2 could be picked off.

Two deuteron groups were resolved, one corresponding to the ground state of P^{30} and the other to a level (or levels) at about 0.8 Mev. The distributions for these two levels are presented in Fig. 23. The fit was considered best for a radius of 5.6×10^{-13} cm, which is quite reasonable for a nucleus of this size. The ground state of P^{31} is known to be $\frac{1}{2}^+$. The ground state of P^{30} is 1^+ and there is a known doublet $(1^+, 0^+)$ at 0.7 Mev. Deuterons from both levels of this doublet may have contributed to the observed excited state distribution. These spin assignments are in agreement with the observed s-wave pickup on P^{31}.

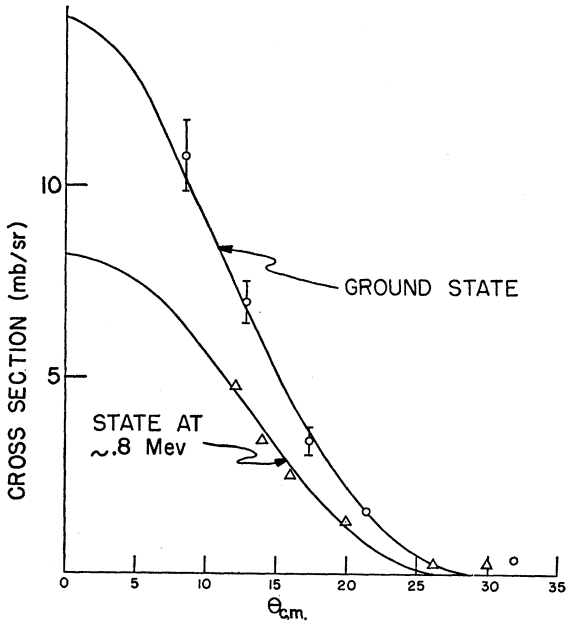

FIG. 23. Angular distribution of deuterons from the reaction $P^{31}(p,d)P^{30}$ leaving P^{30} in an excitation of 0 and 0.8 Mev. Errors shown refer to relative values. $E=18.6$ Mev, $l=0$, and $r_0=5.6\times10^{-13}$ cm.

The ratio of level widths is

$$\frac{S^*I^*[P^{31}(p,d)P^{30}\ 0.8\ \text{Mev}]}{SI[P^{31}(p,d)P^{30}\ \text{ground}]}=0.75.$$

IV. SUMMARY

In Table I we list values of level-width ratios for the experiments reported here.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the continued interest and assistance of Professor R. Sherr and Professor G. Schrank. I thank Dr. M. Banerjee and Dr. John Blair for their valuable comments and Dr. M. Macfarlane and Professor J. French for providing the results of their research prior to publication and for pointing out a mistake in the calculation of the C^{13} wave function. I thank Dr. R. Detenbeck for his generous assistance in maintaining and operating the two-dimensional analyzer. The experience of Dr. J. Likely and Dr. J. Reynolds was freely solicited in the early stages and was of great value.